

ENGINEERING EXPERIMENT STATION

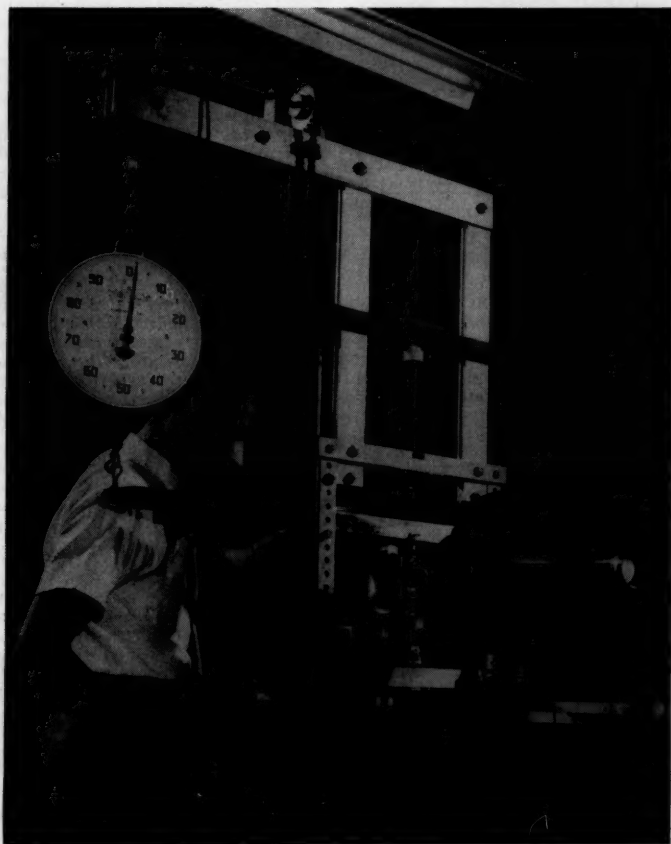
The Research Engineer

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RESEARCH REVOLUTION

A century ago the average working man put in twice the on-job time of his counterpart today. At least half of our nation's present working population earns its living producing things unknown fifty years ago. Technological progress has, as a noted industrialist recently put it, "had a more profound effect upon social custom and social reform than any legislation."

This quotation would surprise the "prophets" of yesteryear who warned that technology would make displaced persons of the working population. Instead, it has brought an unparalleled standard of living for all—more and better paying jobs, less work and more leisure, new and better things for our use and enjoyment.

Facing a new year, early in the second half of the Twentieth Century, we cannot help wondering what life will be like in 2003 or 2053. One thing seems sure—whatever more bountiful life awaits our children will largely be the work of the greatest revolutionary force of all, research. For the pure researchers who provide new knowledge and the applied researchers who adapt it to practical use are the source of technological progress.

One particularly competent researcher, like a unique idea, is worth a dozen mediocre ones. Such a man and the new knowledge he is capable of bringing into the world are the stuff that progress is made of—hitherto unknown products, processes and industries, better livelihoods and higher standards of living for men.

In educators, too, quality is the priceless factor that sets the few above the many. A superior teacher stimulates the student's mind to inquiry, opens existing knowledge to him and encourages him to seek new answers where he finds the old inadequate.

The superior, by definition, is not common, and demand for exceptionally fine researchers and teachers will always exceed the limited supply. Unfortunately for the universities, where such men are most needed, demand, in its economic sense, requires the ability to purchase as well as the desire.

Too often we lose, or fail to acquire, brilliant men because we cannot bid in the same salary market with industry.

In the end it is the public that loses when universities cannot engage the best minds available. When men of demonstrated teaching and research skill are drained from the campus, young minds lie uncultivated and the fields of industrial development produce nothing basically new for want of fresh ideas.

State-supported institutions are, in general, both the least able to employ outstanding men and the most susceptible to rectification of this disadvantage. The public, acting through its legislators, can insure superior educations for its children and the continuing fruits of basic research to posterity.

BLAKE R. VAN LEER

President, Georgia Institute of Technology

EXPERIMENTAL STRESS ANALYSIS

By J. P. VIDOSIC*

Experimental stress analysis is a powerful tool for determining the strength of the components of machines and structures. Not only does it make possible the analysis of stress problems not solvable by present theories, but it often yields solutions more simply and quickly than does the theoretical approach. In addition, it provides data for the development of new and more powerful theories. This article discusses some of the applications of experimental stress analysis and describes the methods now in use.

Stress analysis, a distinct branch of professional engineering, has as its object determination of the mechanical strength of machine and structure components. This is accomplished analytically using either the methods of elementary strength of materials or the more powerful theories of elasticity. Where rigorous mathematical solutions are not always available, one turns to mathematical approximations for a solution. However, it is surprising how quickly our present ability to solve stress problems mathematically reaches its limit. There are a multitude of comparatively simple but practically occurring stress problems for which mathematical solutions are not available. To solve them we must turn to experimental methods.

Thus, experimentation is widely used in stress analysis, as it is in other branches of science and engineering. However, the experimental approach must not be assumed to serve as a mere counterpart of the theoretical method. Instead, it encompasses theoretical solutions, supplementing as well as complementing them. It utilizes all of the conclusions reached by theoretical considerations and then goes beyond them to maintain the direct contact with actual physical phenomena so necessary in the development of new theories as well as in the solution of existing stress problems.

Even our best theories involve assumptions which simplify and idealize the case in order to make the problem solvable. In practice, ideal situations rarely exist. The experimental method allows us to ascertain whether the assumptions have excessively distorted the essential features of the stress problem, particularly if we conduct the test under actual service conditions with

all the factors present. In addition, the experimental approach permits determination of the stress distribution in a part under operation without any knowledge of the forces acting. Thus, experimental stress analysis offers a great and most important advantage over the theoretical approach, because a numerical solution to any stress problem is mathematically not possible without knowledge of the exact forces acting. From the practical point of view, the greatest advantage of experimentally analyzed design probably is that it results in better material distribution. By revealing the weaker portions of a part, as well as its areas of relative overstrength, the experimental approach enables us to modify its proportions until a more efficient design, utilizing a more uniform and more economical margin of safety, is attained.

Experimental stress analysis received its early impetus around 1920 when the devel-

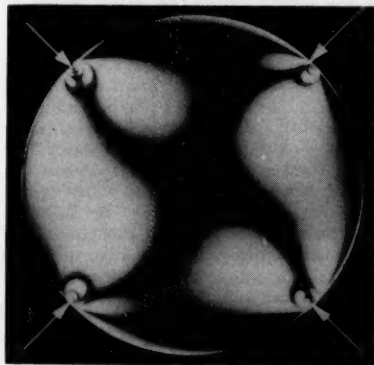


Figure 1. In the photoelastic method, distortions set up in a transparent model cause double diffraction of polarized light, giving a pattern showing the stress distribution.

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opment of Bakelite made the photoelastic method more practical. Since that time, numerous strength problems have been solved by a variety of techniques. A list of problems investigated would range from the study of skull fractures¹ to the measurement of strains on structures subjected to underwater explosions.² Besides solving many a difficult industrial problem, experimental stress analysis has provided data for development of new theories, having been used in both applied and fundamental research.

A look at a few of the investigations that have been made may give some idea of the wide applicability of experimental stress analysis. For example, there is the three-dimensional photoelastic analysis of threaded pipe joints such as are used in the rotary drilling of oil wells.³ Sections of hollow drill shafts are connected into drilling rods (sometimes over a mile in length) by means of tapered-thread pipe joints. These shafts, which are hollow to permit the circulation of "mud" for removing the cuttings, can fail in fatigue. When this happens and a joint fails deep down in the well, it is both difficult and costly to remake the joint. The experimental analysis provided more data relative to the stress distribution within the joint and threads and, after fatigue data already available were checked, more reliable stress concentration factors were established, thereby permitting better design of such joints.

Then there is the fundamental strain gage investigation that was conducted to determine which of the plasticity theories best predicts the actual stress conditions in thin-walled cylinders subjected to a combination of compression and torsion.⁴ The many theories that purportedly explain the plastic behavior of materials under conditions of polyaxial stress may be classified into deformation, flow and slip types. The deformation theory assumes that the state of strain is uniquely determined by the state of stress with the principal strain and stress axes coinciding. The flow theory assumes, on the other hand, that the strain increment is determined by the existing stress, as well as the increment of stress, and that the principal axis of incremental plastic strain coincides with the principal stress axis. The newer slip theory is based

on the assumption that the initial shearing modulus of a material in compression depends on the relative values of the compressive and shearing components of the stress increment. In the investigation, two thin-walled cylinders made of 14S-T4 aluminum alloy were subjected to compression into the plastic range and then twisted. The data obtained did not wholly support any one of the theories. Instead, they indicated that the initial torsional stiffness is best explained by either the flow or the slip theory but that the rotation of the principal axes of plastic strain and the magnitudes of plastic strain are not completely explained by any of the theories.

Where substantial residual stresses exist, they may constitute a large portion of the peak stress in a part. No general theory of the mechanics of residual stresses has yet been developed. Many attempts to study residual stresses by experimental methods have been made. The applications of experimental stress analysis are well illustrated by two studies of residual stresses in large magnesium castings, one using a strain gage method⁵ and the other using a brittle lacquer method.⁶ In the first case, strain gages were employed to measure and analyze the residual stresses in castings in the as-cast, heat-treated and surface-worked conditions using the subdivision technique. (In this method, strain gages are attached to the part and the surface is cut, thus releasing residual stress in the area of the cut. If a residual stress was present, the strain gages will indicate it.) In an effort to develop a more economical method of studying residual stresses, other investigators coated castings with brittle lacquer (Stresscoat), drilled holes in the coated casting to relieve the stresses and studied the Stresscoat cracks thus obtained. Upon comparing their data with those obtained with strain gages, they noted considerable scatter. However, this approach does prove to be more practical than the strain gage subdivision method.

The photoelasticity method has been used to solve basic problems such as that of the maximum stress in an eccentrically curved beam.⁷ A curved beam having the

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ACOUSTIC PHONETICS — AN ENGINEERING APPROACH TO SPEECH

By BENJAMIN J. DASHER*

Applying the methods and tools of science to the field of phonetics, experimenters have demonstrated that speech sounds can be distinguished one from another by certain visibly representable attributes. Their work and its potential applications are briefly described here.

Development of a voice typewriter—a machine that would write a message directly as it is spoken—is one of the more fascinating possibilities of acoustic phonetics. Visual and mechanical aids for the deaf, as well as devices for studying and teaching speech in all its aspects, are among the equally significant, if less spectacular, potentialities of this relatively new, not widely known field.

Books could be (and have been) written on the techniques and applications of acoustic phonetics, even though the field is still in such an experimental stage of development that one hardly knows whether to call it a science or an art. Since its techniques are largely those of science—quantitative measurement and interpretation of data—and its possibilities will require much more research before they become useful applications, a brief discussion of acoustic phonetics seems reasonably appropriate in this publication.

In essence, the field of acoustic phonetics covers the relationship between speech and sound. This relationship is implied in the definition of speech—communication or expression of thoughts in articulate sounds, i.e., spoken words. A word, according to Webster, is the smallest unit of speech that

has meaning when taken by itself. Words are subdivided into syllables, or uninterrupted units of utterance, both in speaking and in writing, the latter at the end of a line where a word must be broken. Phoneticians go further, breaking syllables down into individual sounds called phones. Webster defines a phone as a speech sound which, in any language, can be represented by one or more letters.

An additional distinction is made between the phone, which is a physical phenomenon subject to quantitative measurement, and its close relative, the phoneme, which is a subjective phenomenon representing an interpretation of the sound. A phoneme is defined by Webster as "a group of variants of a speech sound, usually all spelled with the same or equivalent letter and commonly regarded as the same sound, but varying somewhat with the same speaker according to different phonetic conditions (neighboring sounds, stress, length, intonation, etc.). Thus the *l* sounds in *leave*, *feel*, *truly*, *solely*; the *t* sounds in *ten*, *stay*, *try*, *battle*, *cotton*, *city*; or the *e* sounds in *get*, *tell*, *says*, *send*, though organically and acoustically different, belong respectively to the same phoneme, since their variations are due to phonetic environment. Different members of the same phoneme cannot distinguish words otherwise identical; only

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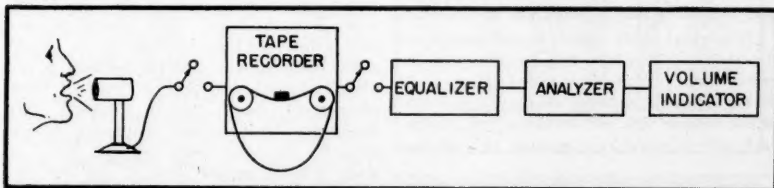


Figure 1. By feeding a sustained sound successively through this equipment and recording its intensity at each frequency, a spectrum analysis is obtained.

members of different phonemes do so, as in *bet*, *bit* or *nod*, *not*. Different sounds may belong to one phoneme in one language and to separate phonemes in another. Thus *ng* and *n* belong to one phoneme in Italian, the *ng* sound only occurring just before *k* or *g* sounds, where the *n* sound never occurs; but in English they belong to separate phonemes, as in *sing* and *sin*."

In normal conversation our attention is focused on words or groups of words rather than on phones or phonemes. Single sounds have no meaning unless associated with words. Yet if we are to develop machines that will "understand" speech (and perhaps reproduce it in writing), we must determine the factors that will permit sounds to be cataloged into phonemes, so that the phonemes can be combined into syllables and the syllables into words.

In order to obtain an exact visual representation of a speech sound every detail of every vibration comprising it would have to be specified. Such a complete representation probably would prove too complicated for practical purposes. Consequently, the acoustic phonetician has attempted to reduce to the minimum the number of characteristics he must take into account in cataloging speech sounds.

While a knowledge of how humans produce speech sounds is essential to the acoustic phonetician, space prohibits its discussion here.* Suffice it to say that, for our purposes, the speech organs may be visualized as comprising an acoustic filter, whose characteristics can be varied over a wide range, together with suitable generators for exciting it. Three types of excitation are available: impulse, random and periodic. Speech is produced by adjusting the filter characteristic to correspond to certain known patterns and supplying the appropriate excitation.

The vocal cords supply sound energy to the oral cavities where it is concentrated in one or more pitch regions called "formants." These formants, determined by the position of the tongue, lips, etc., serve to characterize each speech sound in a manner akin to the

way characteristic overtones distinguish one musical instrument from another.

Using this admittedly oversimplified concept of the speech mechanism, investigators have found that the principal factors to be considered in the acoustic classification of speech sounds are types of excitation and the number and frequencies of the formants. In addition, the relative duration and intensity of the sounds and the manner of their interconnection must be considered. Most sounds possess several typical features that usually, but not always, occur together. Context often implies missing features, permitting words to be identified readily in spite of "errors" in their details; e.g., if one says *git* instead of *get*, no misunderstanding is likely. Some speech sounds are typified more by changes in formant frequencies or intensity than by any specific stationary features.

A brief review of how many of us learned to read may help somewhat, at this point, to clarify what has already been said using the rather specialized terminology of phonetics. This recollection of past experience may also assist us in grasping the principles underlying interpretation of visibly recorded speech sounds—for in a simpler form this principle has long been used to teach reading and, to some extent, spelling.

Let's go back to the days we learned our ABC's. True, we learned them by the *names* of the letters: A, B, C, D, E, F, G, etc. However, many of us also were taught that these letters had one or more *sounds*. For example, A has one sound in *father* and another sound in *late*. We learned that C sounds "hard" in *cat* and "soft" in *circle*.

After we had learned the basic speech sounds—there are about 50 in English—we were able to pronounce some words we had never before seen, simply by "sounding" them letter-by-letter. This system of pronunciation worked imperfectly in many cases, both because English spelling is not always phonetic and because there are fewer phonemes (speech sound variants) than there are basic sounds (phones). Consequently, we were soon (in the third to sixth grades) taught how to use the dictionary to determine the correct pronunciation.

*Additional information on phonetic principles, including the role of the various speech organs, can be found on page xxvii of Webster's New International Dictionary, Second Edition.

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REVIEW OF CALCULATOR OPERATIONS

By HERBERT P. PETERS*

No single service rendered Southeastern industry by Georgia Tech's Engineering Experiment Station probably has more impact on the development of this area and the life of its citizens than does the aid provided electrical power companies in designing transmission and distribution systems. Last year the A-C Network Calculator Laboratory operated at a 95 per cent industrial use factor, with 71 per cent of that time devoted to the expansion problems of Southeastern companies.

November, 1952, marked the fifth anniversary of the installation of an A-C network calculator at Georgia Tech.² These five years have proved the perspicacity of those men who originally provided the calculator equipment and have demonstrated the adequacy of the equipment selected by them.

In the five years of its operation, the network calculator has been used for 145 studies by power companies. These studies, mostly of one or two weeks duration, were conducted for 37 different utility companies. Among the major users of the equipment were the Southern Company subsidiaries (Georgia Power, Alabama Power, Gulf Power, Mississippi Power), Florida Power and Light Company, Philadelphia Electric Company and the Duke Power Company. The remainder of the 37 users include most of the Southeastern companies, several Northern companies and at least five foreign companies. Figure 1 shows graphically the use of the calculator since its installation. This chart indicates a steady increase in its use during the past five years, with a 95 per cent use factor for the past year. At the time of installation, a use factor of 80 per cent was set as a satisfactory goal. The present figure is probably higher than can be maintained indefinitely. Part of this high demand for calculator time is a result of the enormous increase in electrical load in this country in the last few years. During the late war, demand for electrical energy skyrocketed. New equipment was at a premium and the increased load was carried by decreasing standby reserves, by using inefficient equipment and by utilizing diversity between systems through intercon-

nections. It was generally considered that, after the war, energy requirements would fall to prewar values and follow the prewar growth curves. However, this "normalcy" did not develop. Load decreased only slightly and then started to grow at an unprecedented rate. This trend is continuing. Power-system loads are doubling about every six years. To meet these new demands, utility systems are building almost feverishly, and since the design of the electrical system is of necessity made on a network calculator, the use of such equipment has greatly increased. If the often predicted postwar depression should arrive, many power systems may be overbuilt, new construction would stop and, consequently, demand for network calculator time would obviously decrease.

As an outstanding example of the use made of an A-C network calculator, a study just completed by the Duke Power Company may be of interest. Duke is the largest

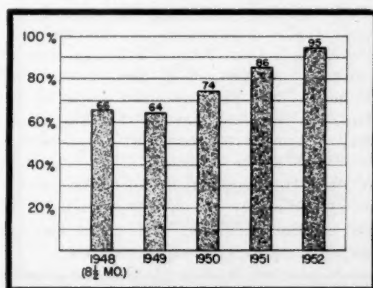


Figure 1. Industry has made increasing use of Tech's A-C network calculator, as this chart of annual use factors indicates.

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single power company in the Southeast, serving the industrial heart of the Carolinas. They have at present a peak load of well over one and a half million kilowatts. As with other companies, their load is increasing and they are making studies of generating and transmission facilities necessary to support two times present day loads. They investigated the opening of five new generating sites in addition to extensions at two of the five major steam plants now in operation. Consideration was given to units of 150,000 and 200,000 kw capacity as well as transmission additions at 100,000 and 230,000 volts. The study of such a problem might include the investigation of a tremendous number of normal conditions, with several alternates and emergencies for each normal. Practical considerations fortunately throw out most of the combinations. In this case Duke investigated 320 cases, normal and emergency, as those most practical. From a comparison of operating costs and capital investment for these alternate conditions will come a final decision as to the location, time of installation of units and necessary auxiliary facilities. The economics of the study does not, of course, come from the network calculator but, rather from the work of the company's engineers. However, the 320 studies of the electrical characteristics of the system were made on our calculator. They required eight weeks, spread over the past year.

Nearer home, the Georgia Power Company has made extensive use of the Georgia Tech calculator. All of the generating stations under construction or recently completed have been located with the help of calculator studies. The most notable of these is Plant Yates, 30 miles south of Atlanta. This plant has 300,000 kw of installed capacity at present, with a possibility of 400,000 kw in the future. The connection of Plant Hammond, at Rome, to the Georgia Power Company system was studied in detail on the calculator. This plant also has an ultimate capacity of 400,000 kw.

At present, the Georgia Power Company and associated companies are making a long-range study to determine whether future expansion will involve new generation in the load areas or whether it is more eco-

nomical to generate power with cheap fuel in large plants in the coal fields and to transmit this power at 287,000 volts to the load centers. In other words, is it cheaper to generate at the coal mine and transport electrical power over wires, or is it cheaper to transport coal by railroad and generate power at the load centers? A study of this type requires a study of the system, expanded to carry the future loads, to determine what equipment, such as line, condensers, etc., will be required under both types of operation and what the power losses will be. Then, from a comparison of capital investment required, energy losses and fuel costs, the over-all economics of the two types of systems can be compared and the best one selected.

The use made of the calculator for these things is tangible. It is used by a customer for so many weeks, and he pays so many dollars. There are other aspects to owning a calculator which are less tangible, but no less important. One of the most important of these intangibles is the value of a calculator to an educational institution. At Georgia Tech the calculator equipment and its full staff are made available, without charge, to the students and faculty for both instructional and research purposes. While our equipment was designed primarily to represent the electrical network of a power system, it is applicable to the solution of any electrical network supplied by a source of constant-frequency, sinusoidal voltage. A candidate for the Master's degree recently investigated the calculator's potential usefulness in solving hydraulic problems by setting up an electrical network analogous to a water transportation system's network of pipes, supply points and discharge points. As a previous literature search has indicated, this method of analogue solution is potentially applicable to a number of fields.⁴ It is anticipated that cooperation with Tech's various schools may develop other studies within the scope of our equipment.

The A-C Network Calculator Laboratory's contribution to the instruction of undergraduate students of electrical engineer-

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COMPUTATION ENGINEERING
AT INDUSTRIAL LEVELS

By W. H. BURROWS*

The applications of computation engineering to industrial problems are not as widely understood and appreciated as their potential value indicates they should be. This article points out how the methods and devices of computation engineering can save time and, consequently, money in industrial plants.

The industrialist who requires the services of an accountant, a chemist, a mechanical engineer or an industrial engineer is generally sufficiently well acquainted with the nature of their services to realize that through them he may arrive at a means of increasing the worth of his product, lowering costs or increasing the efficiency of his employees or machines. Not so with a computation engineer. There are few, if any, industrial organizations of any size that would fail to profit, some quite handsomely, from the services of a computation engineer. However, there are even fewer who realize the existence or understand the nature of such services.

With today's social security finances, union benefits, tax withholdings, employee bond purchasing, etc., no commercial organization would dare attempt to keep its books by the hand-and-brain methods of 1900. Were it not for the development of modern accounting machines, either Congress would have had to forego social legislation (and the tax levies that support it) or we would all have had to forsake our trades to become bookkeepers. The technology which has spared us that fate is an excellent example of what computation engineering can accomplish. Its potentialities extend into the industrial plant in every area where computation of any kind is involved. That it has not been more extensively applied is largely a consequence of an understandable lack of awareness on the part of the industrialist of the nature or availability of computation engineering services. Another contributing factor is that computation in areas outside of accounting is often

scattered in fragments too small to attract much attention until considered in the aggregate. Consequently, methods of calculation in numerous areas of industry are comparable to the bookkeeping methods of several decades past.

The nature of computation engineering is illustrated by Figure 1. The left-of-center portion shows the state of affairs of a typical routine prior to computation engineering study. There is a series of mathematical operations leading to the desired result. Each operation derives from its basic data a result which, except in the case of the final result, becomes a part of the basic data for the next operation. The basic data for each operation consists of either (a) the results of a previous operation, or (b) the entry data for the series. Examples of entry

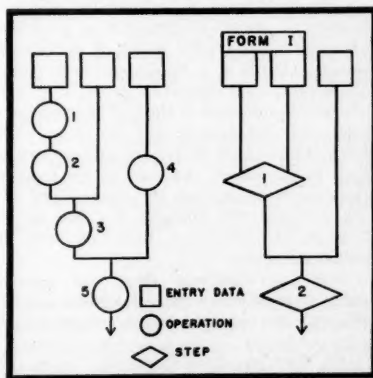


Figure 1. How computation time can be saved by combining several mathematical operations (left) into a smaller number of steps (right) is explained in this article.

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data are: (1) quantitative measurements of product quality, (2) statistical measurements of machine performance, (3) tables of freight rates, (4) price lists and quotations on supplies or raw materials, (5) company discount practices, (6) advertising rates, etc.

Through computation engineering, two time-saving modifications are made. First, the number of steps in the calculation may be reduced by combining several operations into one step, as shown in the right-of-center portion of Figure 1. The means whereby this condensation is effected is shown later in this discussion. Second, the computation engineering study results in a redesign of the associated forms on which the entry data are assembled, the carry-over data from one operation to the next are recorded and the final results are reported. The design of these forms must be made after the sequence of computation steps has been established, for only then is it possible to take into account all of the following factors controlling their design. These factors are: (1) the nature and origin of the basic data, (2) the steps toward which each datum is directed, (3) the nature of the computing device used in each step, and (4) the manner in which the final result is to be presented.

The breakdown of the problem into operations is always as complete as possible; for example, a typical series of operations may be (1) add $a + b$, (2) square the sum, (3) square c , (4) subtract c^2 from $(a + b)^2$, (5) take square root of the difference. Sometimes this breakdown still leaves us with fairly complicated operations on our hands, such as (a) obtain the root of the quartic equation lying between the limits 5 and 15, (b) evaluate the integral for the limits 0 to n , etc., although these are rare at industrial levels.

For each problem there are usually many ways in which the breakdown may be effected. An example is the evaluation of

$$y = \frac{p_x r_x}{p_x r_y + p_y r_x + r_x r_y}$$

Basic data are the constants r_x and r_y and the variables p_x and p_y . The operations may be broken down into four multiplications, an addition (of three terms) and a

division. However, the expression may also be written

$$y = \frac{p_y / r_y}{p_x / r_x + p_y / r_y + 1}$$

involving three divisions (since p_y / r_y appears twice) and one addition, or as

$$y = \frac{r_x / p_x}{(1 + r_y / p_y) (1 + r_x / p_x) - 1}$$

involving three divisions, one multiplication, two additions, and one subtraction.

By considering the various forms of breakdown, it is frequently found that several operations may be reduced to a single step, since (a) tables are available for the combined operations in a given step, such as tables of $(1 + r/p)$ in the above example, (b) a chart or machine is available which performs the computation for the entire step (see Figure 3), or (c) this step occurs in another related problem and its values are available from that source.

Whether for single operations or multiple operations (steps), the function of each computing device may be represented by a mathematical expression, such as $a + b + c + \dots$ for the adding machine, $a \times b$ or $a \div b$ for the "calculating" machine, a^n for the log-log slide rule, or $ax y^n$ for one type of nomograph. Any device whose characteristic expression is identical with that of an operation (or step) may be used for that part of the problem.

The selection of a device for a given step should not, however, be made independently of consideration of the rest of the problem and of other problems of the same organization. It is obviously desirable to keep to a minimum the number of different devices employed in one location or at one time; towards that end it is sometimes desirable to select a computing device with several problems in mind.

Devices commonly employed for computation at industrial levels may be classified as (1) numerical (tables), (2) graphical (cross-section graphs, nomographs), (3) mechanical (adding machine, "calculating" machine, etc.), (4) graphico-mechanical (slide rule, gear rule), and (5) numerico-mechanical (IBM electronic computer and related devices).

Tables, such as the common tables of compound interest for the formula

$A = P (1 + i)^n$,
usually listed only for the value $P = 1$, or tables giving the capacities of horizontal cylindrical tanks with bulged ends for the formula

$$V = 0.0009328 h^2 (3r - h)$$

gallons, are valuable substitutes for computation and are extensively used in computation engineering. Since a great many industrial problems involve tables of such a specialized nature that they are not available in published form, the proper preparation of tables is one of the duties of the computation engineer. Actually this is a double duty; for not only is it necessary to consider the design of the table and its integration with the whole problem, but the actual method of computation to be employed in constructing the table is, itself, often a computation engineering problem.

The table should be constructed so as to avoid the necessity of interpolation insofar as that is possible, since interpolation, especially non-linear interpolation, is merely the substitution of one computation for another. Many tables consist of discrete entries for which interpolated values have no meaning. Where interpolation is unavoidable, a mechanism, such as an auxiliary table of proportional parts, is frequently included to facilitate interpolation. Otherwise, inaccuracies are likely to vitiate the real accuracy of the table.

Because of the bulkiness necessary in some tables if excessive interpolation is to be avoided, other means of representation should be considered before a final decision is made. This is especially true in the case of steps involving more than two variables. It often happens that a graphical method of representation is less space-consuming than a table, yet it may provide an equal degree of accuracy plus ease of interpolation.

The techniques involved in constructing graphs, nomographs and slide rules were discussed in a previous article in this publication.* The graph is, of course, the most familiar and, in its usual form, the least useful as a computing device. However, in the Engineering Experiment Station's project on graphical and mechanical methods,

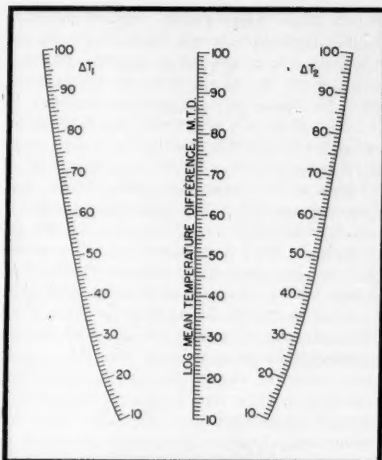


Figure 2. This nomograph substitutes one operation, laying a straight edge between two points, for consulting logarithm tables, making two subtractions and one division.

modifications of the graph have recently been developed, which increase greatly the capacity of this device as a computing aid. The modified graph has been successfully applied to several difficult problems and has been shown to provide, on an equal-space basis, at least as much accuracy as a table and much greater ease of interpolation. These modified graphs will be described in a later article.

For expressions relating several variables, the nomograph is frequently the most satisfactory device. Figure 2 shows a nomograph for determining the log mean temperature difference which equals

$$\frac{T_2 - T_1}{\ln T_2 - \ln T_1}$$

Here, one operation, the laying of a straight edge between two points, substitutes for reading two numbers from logarithm tables, making two subtractions and one division.

Of all the devices employed in computation engineering, the modified graph and the nomograph alone possess the necessary properties for incorporation into the work

*Burrows, W. H., "Graphical and Mechanical Methods of Computation," *The Research Engineer* 1949-50, No. 5.

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sheets of a computation step. This is a highly desirable feature in some problems; the data, the computation and the final result are all on a single sheet in a form suitable for filing as a permanent record.

The slide rule and the gear rule provide solutions of the expression $a + b = c + d$ if linear scales are used or $a \times b = c \times d$ if logarithmic scales are used. Scales constructed on other functions are used for special slide rules, such as that shown in Figure 3. The convenience of these rules gives them a measure of popular appeal that makes them effective advertising novelties.

The gear rule, in its simplest form, consists of scales mounted on disks or drums connected by gears so as to move in accordance with the expressions in the preceding paragraph. However, the gear rule possesses several advantages over the slide rule. By using spiral scales wound on a drum, it is possible to have scales of one hundred or more inches in length, thereby increasing greatly the range and accuracy of the scales. By using cross-linkages in the gear mechanism, it is possible to introduce a more involved mathematical expression than that given for the simple form, $a + b = c + d$. Sometimes cams, bar linkages, etc., are used in conjunction with the gear mechanism to provide special mathematical relations. Also, as with the slide rule, the introduction of special scales provides a means of representing mathematical expressions other than those of addition or multiplication.

Such are the devices which the computation engineer may design and construct as

aids in an industrial routine. Very frequently they provide the simplest and most direct method for handling a problem. They are especially a boon when the industrial organization does not already have a sufficient investment in mechanical calculating equipment that can be diverted to the routine in question or when the routine employing mechanical equipment is much more complicated than that based on numerical or graphical devices. However, the need for keeping the number of different devices for a given place and time at a minimum must always be kept in mind, as must, also, the fact that there are many industrial problems in which the mechanical method is highly satisfactory. A thorough computation engineering study is indicated as a means toward making more efficient use of the equipment on hand. After all, the selection of the equipment is only one phase of computation engineering service.

Case Studies

The results to be expected from a computation engineering study in the plant are indicated by the following experiences of actual cases.

One company had for years used the time of one of its executives for a very time-consuming problem. It had not been found feasible to attempt to train clerical help because of the complexities of the problem. Following the study it was possible for the company to turn the job over to clerical help with very little training. The job was done much faster, and the results—which

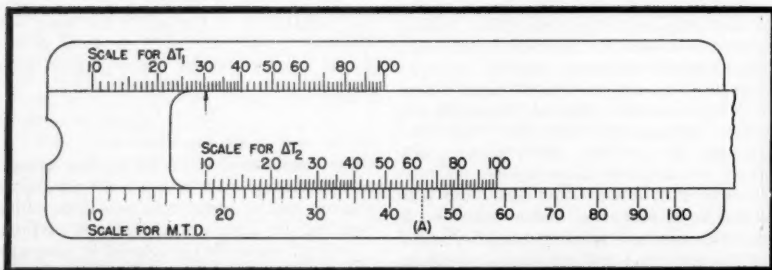


Figure 3. Special slide rules can, like nomographs, be designed to shorten the time of computation operations. This one has all the advantages of the nomograph shown in Figure 2.

EXPERIMENT STATION RESEARCH ENGINEER

had always been in doubt before—were much more profitable to the company.

Another company, about to engage in a new type of testing of its raw material, planned to purchase an expensive piece of mechanical calculating equipment for converting the test results into meaningful terms. A simple graphical device, costing less than two per cent as much as the machine would have cost, actually performed the same computation in about one-third the time it would have required and with the full degree of accuracy desired.

Still another company, engaged in a chemical process in which the composition of certain baths had to be maintained uniform, had been taking samples from the baths at regular intervals, making an on-

the-spot analysis, then sending the analysis to the front office for mathematical interpretation before making the necessary adjustment in the composition of the liquors. A computation engineering study resulted in a series of charts that provided on-the-spot conversion of test results into adjustment requirements. Thus, the adjustments could be made immediately.

The clerk, the laboratory technician and the man on the assembly line all become their own mathematicians with a properly established routine and the right devices for effecting the computation. Periods of in-service training are shortened at a saving to the company. And both the number of errors and the time spent in computation are reduced.

REVIEW OF CALCULATOR OPERATIONS

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ing is limited primarily by their already full scholastic schedule and consists, for the most part, of exhibiting the equipment to them and explaining its operation and applications. However, our participation in the training of graduate students is one of the most satisfactory aspects of our work. At the time the calculator was purchased, the Westinghouse Electric Corporation gave to the Alumni Foundation \$15,000 to be used for fellowships in electrical engineering. These fellowships have been given to two men each year since 1947, and each carries a stipend of \$1,250 per year. The students spend approximately half their time in work toward a Master's degree and half in operating the calculator. Thus, they have the advantage of learning the practical operation of power systems, meeting the engineers representing the various power companies and generally learning the "language" of the industry. To quote from *The Christian Science Monitor*, "Some students acquire knowledge, others develop ingenuity and resourcefulness. Young Tucker was definitely in the latter class. One question of his exam read: 'What steps would you take in determining the height of a building, using an aneroid barometer?' To which the

young man blithely replied, 'I would lower the barometer by a string and measure the string.'" While it is necessary to know how to calculate engineering problems accurately, the graduate will find that, in industry, one very often "measures the string." We feel that the practical experience the Fellows gain in working on commercial problems is of great benefit to them in their careers. This has been borne out by the positions these men have taken following their graduation. Sixty per cent of them are now in system-planning work for various companies in this area, all acquiring their positions through contacts made during their calculator experience.

The funds initially supplied by Westinghouse for fellowships will be exhausted in the near future. An attempt will be made to have the fellowships continued through support of the power companies in the Southeast. It is felt that the small investment required will be more than recovered in the direct benefit derived from training engineers specifically in power system operation and in the indirect benefits to be derived from the encouragement of engineering education in general.

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The calculator equipment, as installed in 1947, is still proving adequate for today's needs. The only addition to the equipment has been installation of load-adjusting voltmeters on the 60 load circuits.³ These were installed in 1949 and have proved to be an enormous timesaver. There is a possibility that varmeters will be added soon to give a full complement of generator instruments. Certain other improvements of undetermined merit, such as a new type of load circuit and new-type plug-boards have appeared on the more recent Westinghouse calculators. However, at the present time their cost appears to be out of proportion to their value. Some of our customers have expressed a desire for more equipment, particularly generator circuits and pi-line units. Space can be made available for this equipment. Should the demand for it increase and the necessary funds be made available, it is possible that the size of the installation may be increased in the future.

The maintenance required on the calculator has been very small. This is typical of the Westinghouse calculator, which employs a high power base with the resultant rugged equipment and makes minimum use of electronic circuits. The small amount of maintenance required accounts, in part, for the large amount of time the Georgia Tech calculator has been available for commercial usage.

Since the installation of the Georgia Tech calculator, nine new calculators have been installed in this country, raising the total number to 26. Of the nine new calculators, six have been installed by power companies and three by universities. The University of California has installed a small calculator for educational use. The University of Illinois and Northwestern University have installed calculators of commercial size. It is interesting to note that in the last two cases the equipment was designed and built by the school and the standard calculator frequencies of 440 and 480 cycles per second were not used. The University of Illinois² calculator employs 10,000 cycles which permits a reduction in the size of reactors and capacitors and operation at a very low power level. The Northwestern calculator¹ operates at 120

cycles, uses conjugate impedances and operates at a low power level. The advantage of these two calculators is claimed to be low cost, although their costs are figured on the basis of material and low labor charges, with engineering time ignored. These special calculators have the disadvantage (to the power engineer) of requiring a large number of electronic circuits, which necessitate considerable checking and maintenance.

Although it is not directly a calculator function, the annual Georgia Tech Conference on Protective Relaying has been a direct outgrowth of the acquisition of the calculator. The calculator personnel have been very closely associated with the four conferences so far held and will probably continue to be active in the future meetings. This conference brings together the relay engineers, particularly those in the Southeast, to exchange ideas and to learn what is new in the industry. Each meeting has been attended by about 100 engineers, which is a good representation for the limited field of interest.

Summing up the first five years of operation, the A-C Network Calculator Laboratory appears to have played a useful part in the continued progress of Georgia Institute of Technology and in that institution's services to the industry of this area. It is still one of the largest, most modern and most desirable calculators available. We feel that we are making a valuable contribution to the development of the Southeast by assisting in planning of the adequate electric power transmission and distribution systems so vital to the development of industry and agriculture in any area. That this feeling is reciprocated is indicated by the increasing demand for calculator time made by Southeastern companies; last year work for them constituted 71 per cent of the total time our calculator was in operation.

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STRESS ANALYSIS

Continued from Page 4

same center for its outside and inside boundaries can be solved by the Winkler-Bach theory. However, this theory fails when the centers are separated. The photoelastic investigation in question provided a rational solution for the eccentric beam as well as stress factors which can be applied to a straight beam of identical cross section to yield the maximum stress in the curved beam.

The technique of testing scaled-down structural models of proper similitude to the full-scale prototype has long been employed in the field of stress analysis to ascertain the feasibility of a certain design. Normally, the models have been made of metallic materials. However, construction of such models from plastics has been shown to be not only satisfactory but advantageous in some cases. For example, the use of cellulose acetate and methyl methacrylate to fabricate models of a gun turret and a low-pressure steam turbine permitted cementing of the several components together to obtain the finished complex models, a method offering a definite advantage over the casting process that would have been required in making metal models. The appropriateness and rigidity of the designs were tested by measuring deflections at various critical points by means of sensitive dial gages. In this investigation, the experimenters⁸ established techniques for overcoming the errors resulting from creep, temperature variation and aging of the cemented joints.

Machining operations require suitable speeds, cuts of the correct depth and tools of proper shape. A change in any of these conditions results in a change in the tool forces acting, in the amount of heat being generated and in the nature of the surface

finish. Thus, it is important to study and control the effective factors. Successful dynamometers embodying strain gages have been developed for the purpose of measuring the forces, torques and moments transferred through the tool in turning, planing, milling, drilling and grinding operations.⁹ Bridge circuits best suited for making measurements with these dynamometers are described in the reference cited here.

Strain gages cemented to the pylon of an artificial leg worn by an amputee and to the force plate upon which he walked have been used in a study of the forces acting on the human body during locomotion.¹⁰ Such studies reveal data useful in calculations of muscular work, in the design of artificial legs and in the improvement of surgical techniques.

Photoelastic determinations of the maximum stresses occurring in shafts having keyways when they are subjected to torsion have been found to check closely with those tediously computed by numerical solution of the stress-function differential equation.¹¹ Stresses in shafts with keyways were found to be as much as four times those in keyless shafts.

And so the list could go on and on, enumerating an endless number of applications to which experimental methods have been put. Some of the studies have been fundamental in nature; others have been applied. Some have been researches into the unknown; others, solutions of old problems. No matter what the stress problem, or what the exact technique, all have added to the store of knowledge that the elastician or the stress analyst or the designer can call upon to help him solve new problems and simplify old ones.

Experimental Methods

Many techniques have been developed for the experimental determination of stresses. Perhaps these techniques should be called strain analyses, since the effect normally depends on the phenomenon of yield under load, i.e., deformation or strain. The methods of experimental stress analysis that have been used are as follows:

1. Photoelasticity
2. Strain-gage

3. Brittle lacquer

Since the remaining methods are not to be discussed in more detail, a brief description is included with each as it is named.

4. Brittle models—fracture of the model must occur without appreciable deformation and at a definite tensile stress. The test results are usually interpreted by using the statistical concept that the fracture strength is an unfavorable coincidence of stress intensity and defective material.
5. Structural models—usually linear deflections are measured on a scale model of the proper similitude to the prototype. The loading is similar to that of the prototype in the direct method. However, it may be quite different in the indirect method which therefore concerns itself with the location and study of influence lines.
6. Analogies—when the characteristics of two apparently different systems are represented by the same fundamental mathematical form, a study of one, which for one reason or another might be easier, will reveal information applying to the other as well. This is the well-known basis of analogue computers, as well as the governing concept in soap-film studies of torsional stresses.
7. X-ray analysis—rays of known wave length are reflected by a stressed specimen in patterns which are dependent upon the spacing between planes of atoms in the specimen, which spacing varies with the stress conditions.
8. Photogrid—a fine grid is photographed on an emulsion applied to the specimen surface. The grid system deforms upon application of load to the specimen, thus revealing the plastic strain distribution.

These and probably other methods of specialized value have all been used in experimental stress studies. However, the first three techniques are more easily handled, require less expensive equipment and provide data which can be interpreted with greater facility and accuracy. As a result, they have been tested so thoroughly and developed so extensively that their application to any and all stress problems is feasible economically as well as technically.

Photoelasticity

The photoelastic effect was discovered by David Brewster in 1812 when he found that the optical properties of clear glass are altered when it is deformed or stressed. However, the importance of this observation as an engineering tool was not fully recognized until about the start of the present century, and little application of the photoelastic effect was made until around 1920. Most of the developmental work in its theoretical aspects, in the equipment employed and in the technique itself has been performed since that time. The photoelastic method is thus relatively new. Yet, it is the oldest of the three commonly used methods being discussed.

The optical phenomena involved in the photoelastic method are best explained by the transverse wave theory of Fresnel. Reflection, polarization and interference take place as the light wave propagates through the photoelastic apparatus, commonly called the polariscope. Furthermore, double refraction is occurring within the strained specimen model (and the quarter-wave plates). When the light ray strikes the surface of the strained model, it is broken into two component waves. One wave, called the ordinary ray, traverses the model as it normally should, while the other wave, called the extraordinary ray, is deviated and travels through with a different speed. Each of these waves is plane polarized. This same phenomenon is known to take place in anisotropic crystals such as calcite. The strained model acts like such a crystal, but it is only temporarily doubly refracting, this property disappearing as soon as the strain is removed. The component waves travel through the model along the principal axes at a rate proportional to the degree of straining present. Upon emerging on the far side, the two component waves recombine out of phase to cause interference depicted by dark and light bands. These bands constitute the fringe pattern of the exact stress distribution. This can be expressed mathematically by means of the stress-optic law,

$$\frac{p - q}{2} = \tau = \frac{nf}{t}$$

where p is the maximum principal stress, q is the minimum principal stress, τ is the

maximum shearing stress, n is the fringe order, i.e., the number of times that a fringe has reappeared at a particular point, f is the material's fringe constant measured in pounds per inch of thickness per fringe order, and t is the thickness of the model.

The polariscope mentioned above consists of various elements designed to produce polarized light and analyze it. Each of the elements may be seen on the cover photograph of the apparatus at Georgia Tech. It should be pointed out that the loading frame has been modified with a dynamometer scale to facilitate reading of the load on the specimen and to eliminate the effect of creep on the photoelastic-fringe pattern.

The model for a photoelastic investigation must possess certain optical properties in addition to suitable mechanical properties. Among these is the all-important characteristic that it be transparent as well as optically sensitive to polarized light. Only about a dozen of the commercially available plastics have the required properties, and only about six have these properties to a sufficient degree to make them suitable as model materials.²² Of these Bakelite 61-893, Fosterite and an allyl resin, CR-39, have been found best.

Plastics are, in general, difficult to machine; they chip easily and they assume residual stresses along the edges of the model in the form of time-edge effects. As a result, fabrication of the plastic model becomes a very critical step in the photoelastic investigation. Furthermore, for precise results, the model must be investigated almost immediately after it is machined, i.e., before the edges have had an opportunity to cure further and assume some of the edge stresses mentioned. Except for the care that must be exercised relative to the difficulties discussed, the machining of plastics may be performed with ordinary machine tools.

As mentioned, double refraction of a polarized monochromatic light front, such as that occurring within the plastic model, results in a series of dark interference bands called the fringe pattern. If the light source is white, containing all frequencies, the resulting isochromatic pattern will consist of a glamorous but less useful system of rainbow colored fringes.

When the quarter-wave plates are removed from the polariscope, the light is plane polarized, with the result that vibrations in a specific plane are recorded along with the fringe pattern. This effect can be utilized in stress analysis, since such vibrations establish the isoclinics or the directions of the principal stress planes through a point on the model. The polariscope thus yields two important sets of data: the fringe pattern giving the difference between the maximum stresses in accordance with the stress optic law; and the isoclinics defining the direction of these stresses. Consequently, the photoelastic technique gives all the information necessary to accomplish a complete stress analysis. And this applies to three-dimensional as well as two-dimensional stress fields. In the three-dimensional problem, the stress pattern is first "frozen" into the specimen which is then sliced and similarly investigated with the polariscope.

It must be remembered, however, that the fringe pattern yields the difference between the principal stresses rather than each stress. Along the edges, which usually contain the maximum stress, one principal stress is zero. There the difference reduces to one stress directly. Elsewhere, the principal stresses must be separated by long, tedious numerical computation. Where other tools are available, such as a lateral strain gage, additional data can be obtained to simplify and shorten the task of stress separation.

Since the stress distribution in a singly connected body does not depend upon the elastic properties of the material, it follows that the distribution observed in a plastic model holds for its metallic prototype as well. Elastic theories governing multiconnected bodies sometimes contain elastic constants such as Poisson's ratio, implying a change in the stress distribution with material. Even there, this change is often of such small magnitude that it becomes negligible in most practical cases. Hence, the fringe pattern may be considered the visual picture of the stress distribution, regardless of the material of which the prototype is to be made.

Electrical Resistance Strain Gages

Around 1938, Simons of the California

Institute of Technology and Ruge of the Massachusetts Institute of Technology developed the idea of bonding a wire grid to the specimen, thereby forcing it to take the deformations to which the specimen may be subjected. This would cause a change in the resistance of the wire grid directly proportional to the strain imposed. The result of their investigations is the modern bonded-wire strain gage popularly known as the SR-4 gage. (The Baldwin Locomotive Works, which bought the rights for its manufacture, is still the sole producer of a satisfactory bonded-wire gage.) Unbonded electrical-resistance wire gages have also been developed, but these have not experienced the popularity of the bonded type. In addition, gages depending upon a change in inductance and upon a change in capacitance are available, but again their applications are limited.

The SR-4 strain gages are made in a series of gage lengths from 1/16 inch to 2 inches. They are made of advance metal, Constantan and isoelectric material in one-dimensional, two-dimensional and rosette grids for dynamic as well as static load conditions. The resistance in any of these grids is defined by the well established equation,

$$R = \rho \frac{l}{A}$$

where ρ is the resistivity of the wire material, l is the length of the wire and A is the cross-sectional area of the wire. The relationship between the change in resistance and the strain causing it is expressed by a term called the gage factor. This is derived as follows:

$$G.F. = \frac{\Delta R/R}{\Delta l/l} = \frac{\Delta R}{R\epsilon}$$

where ΔR is the change in resistance of the strain gage produced by the strain ϵ , R is the unstrained resistance of the gage and ϵ is the unit strain of the gage and, in turn, of the specimen to which it is bonded.

Thus, in order to determine the strain we must know the gage factor as well as the unstrained resistance of the gage being used, both of which are precisely given by the SR-4 manufacturer. We then proceed to measure the resistance change occurring when the specimen to which the gage is

bonded is loaded, strained, or stressed. This change in resistance can be measured by means of a potentiometer or a bridge. Many types and makes of bridges are available, some being of the indicating type and others of the recording type. For static conditions, direct-current bridges using the null balancing method are popular. For dynamic loads, alternating-current bridges, combined with circuits to amplify the potential drop caused by the change in gage resistance, are used. In each of these bridges, the strained gage becomes one leg in the circuit. In static measurements particularly, a dummy gage is inserted as another leg of the bridge in order that changes in resistance due to temperature variation are compensated for. Switching devices are available for quickly or even simultaneously measuring a series of active gages. Gages must, of course, be properly selected and well mounted with a cement satisfactory for the conditions to be encountered.

The measurements made are generally strains which are then converted into stresses by means of Hooke's law. Certain easily made corrections are necessary in the case of these bonded gages because of the loss of effectiveness of the wire which forms the loops in the grid. Transverse, axial and cross-sensitivity factors supplied by the manufacturer are used in making these corrections. In biaxial stress fields, strains must be measured in each of the principal stress directions if the maximum combined stresses are to be found.

A review of the equations that define the principal stresses p and q will reveal the fact that the strains ϵ_p as well as ϵ_q are involved. The equations follow:

$$p = \frac{E}{1 - \mu^2} (\epsilon_p + \mu \epsilon_q)$$

$$q = \frac{E}{1 - \mu^2} (\epsilon_q + \mu \epsilon_p)$$

Although not mentioned previously, it is no doubt evident that the gages must be properly oriented with respect to the principal directions. In an unexplored, multi-axial stress field these directions are unknown. There are two ways of attacking the problem. The principal directions may be located by means of a preliminary brittle-

lacquer investigation, or the field may be studied with strain rosettes. Strain rosettes are combinations of two or more gages oriented in different directions. By simultaneously reading the strain in each direction and by using it along with the angles involved in the rosette pattern, the principal directions as well as stresses may be computed. The gages can be cemented to an actual structure and the stresses obtained directly without the use of a model. However, only surface stresses are readily measured with strain gages.

SR-4 gages have been incorporated into sensitive instruments designed to measure many of the entities involved in engineering work. Pressure, temperature, force, torque, vibration amplitude, bending moment, etc., are readily determined by use of these devices.

The Brittle-Lacquer Method

Brittle coatings may be used as strain indicators, since the rupture of such coatings reveals the strain in the underlying material. The first record of such use of brittle resinous coatings appears in the technical literature of 1925. Many coatings have since been tried but the most suitable found yet are the "Stresscoat" series introduced by the Magnaflux Corporation around 1940.

These coatings are quite sensitive to changes in humidity and temperature. As a result, a series of seven Stresscoats has been developed. The proper coating is selected after atmospheric conditions have been established by means of a chart supplied by the manufacturer. The lacquer is then sprayed uniformly upon the surface of the part to be investigated and is allowed to dry under reasonably similar atmospheric conditions. Where the surface of the test piece is dull, it is wise to first apply a bright aluminum undercoating which assists in making the rupture cracks more conspicuous. A dye etchant is also supplied which may be applied to the crack pattern to emphasize the cracks.

When the brittle coating has dried, the part is ready for the strain investigation. Upon application of a tensile stress field to the test piece, which is applied according to the shape and kind of member, the brittle coating begins to rupture or crack

in a series of fine lines. These lines take a direction at right angles to the maximum principal stress. Such a series of cracks, representing the area where the coating has been subjected to its limiting strain, is called an isostatic pattern in brittle-lacquer terminology. In addition, the limit of propagation of the cracks upon successive increase of load may be marked on the specimen. Such marks bound the line along which the extensional strains are approximately the same. These lines are called isoeontatic or equal-stretch lines. Thus, the rupture pattern depicts for us areas of high stress and thereby gives us a qualitatively good picture of the stress distribution on the surface of our specimen. Since the lacquer may be readily sprayed on the surface of even the most complex part, all machine and structural members are susceptible to this method of stress analysis.

The brittle-lacquer method does not give as good quantitative results as do the previously discussed methods. A calibration bar, sprayed and dried along with the test piece, may be used in a quantitative approximation of the stress magnitude. This bar is strained as a cantilever beam by bending in a device provided for the purpose. When the bar is placed in a strain-graduated holder, the approximate unit strain can be detected from marks on the holding frame. The closer the spacing and more intense the cracks along the bar as the fixed end is approached, the higher the strain. In addition, the first cracks mark the threshold sensitivity of the lacquer, which is generally somewhere in the neighborhood of 0.0007 inch per inch. The cracks on this calibration bar are then matched against those on the test piece for a quantitative approximation.

In addition to the fact that the brittle-lacquer method yields only approximate quantitative results, there is still a question relative to the correct explanation and theory of the Stresscoat rupture. It was first believed that rupture of the coating is caused by maximum strain defined by Hooke's law as $s = E\epsilon = p - \mu q$. Lately experimenters have questioned this. Durelli¹² has found indications, though not conclusive ones, that fracture is defined by a law expressed thus:

$$(\mu^c - \mu^s) \frac{P}{E_e} \left(\frac{q}{E} \right)^s + \frac{P}{E_e} = 1,$$

where μ^c is Poisson's ratio for the coating, μ^s is Poisson's ratio for the specimen and all other terms apply to the specimen.

Regardless of its lower quantitative value, the brittle-lacquer method constitutes an important tool for experimental stress analysis.¹⁴ The isostatic pattern certainly reveals areas of high stress, indicates pictorially the stress distribution and gives approximately the magnitude of maximum stresses. The value of a design can be ascertained by Stresscoat analysis; if necessary, the design can be modified and the patterns compared for relative value.

Stresscoat analysis also has its complementary use in strain-gage techniques. As mentioned, strain gages must be oriented in the direction of a principal strain. In an unstudied stress field, this direction is unknown. Strain rosettes can be used to determine it, but so can the Stresscoat technique. A light load on the coated part will cause the isostatic cracks which, as stated, are normal to the maximum tensile stress. The coating may then be removed and the strain gage cemented in the correct direction.

* * * * *

Experimental stress analysis is a relatively new tool, still in its infancy, but it has already contributed substantially to the solution of numerous difficult stress problems of engineering importance. It is here to stay. We at Tech are attempting to assist in its further development and application.

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ACOUSTIC PHONETICS

Continued from Page 6

tion from symbols placed over the letters of a word and its respelling in phonetic form. For example, if we did not know how to pronounce pneumonia, we found it respelled as nū-mōn'ē-ā in the dictionary.

Thus, it appears that most of us are more familiar with phonetic symbols and methods than we might at first think. Professional phoneticians have, of course, developed many systems of phonetic symbols to denote speech sounds, some of them considerably more advanced than the system used in Webster. Acoustic phoneticians have learned to record speech sounds in visible forms such that they can be "read" by those trained in their interpretation. The remainder of this article will be devoted to the methods and applications of acoustic phonetics.

Making Speech Visible

There is considerable evidence that the ear effects a spectrum analysis of speech sounds; that is, it breaks down an oscillation into its various frequency components and perceives their relative amplitudes. Thus, it seems logical to expect that a visible spectrum of a sound may be subject to analysis by the eye. Let us, then, examine a fairly simple means of obtaining visible spectra of speech sounds and see what features can be used to distinguish one from another.

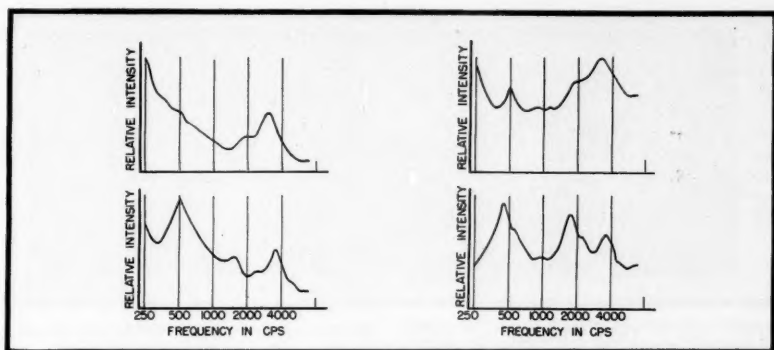


Figure 2. Spectrum analysis of two vowel sounds. At the left, the spectra recorded by the analyzer for the long-E in *see* (above) and the short-E in *set* (below). At the right, spectra of the same sounds modified by the equalizer to simulate the sounds as heard by the ear.

From our knowledge of physics we know that a sinusoidal oscillation is characterized completely by its amplitude, phase and frequency. More complicated oscillations can be considered as superpositions of sinusoidal oscillations.

In order to simplify our first approach to the visible analysis of speech sounds, we shall choose a few specific vowel sounds for spectrum analysis. Since vowels are sustained sounds having relatively stationary features, they are the easiest speech sounds to study.

Our equipment permits us to break a given vowel sound into its components at numerous frequencies and to measure the intensity of each frequency component. As can be seen in Figure 1, a vowel sound is spoken into a tape recorder which is then used to repeat the sound, identically each time, into the analyzing portion of the over-all device. The analyzer is equipped with a number of selector switches so that the input sound can be passed through any one of 30 electrical resonators each adjusted to respond to one particular frequency. These frequencies have been selected so that proceeding from one resonator to the next is equivalent to moving one whole tone on the equally tempered musical scale. The lowest frequency used is 250 cycles per second, corresponding approximately to middle C on the scale, while the highest is 7136 cps,

about one octave higher than the highest C on an 88-key piano. When the sound is passed through one of the resonators, the volume indicator registers the energy (intensity) present at that frequency.

By playing the recorded sound over and over, successively feeding it through the next higher frequency resonator, data are obtained for plotting the relative intensity of each frequency component. Figure 2 shows charts so plotted for two vowel sounds. At the top left, we see the long-E sound that occurs in *see*. This may be represented by the phonetic symbol *i*. At the bottom left is the chart of the short-E sound in *set*, represented phonetically as *e*. As can be seen, the intensities of the high-frequency formants are much less than those of the low-frequency formants. However, formants in the two frequency regions appear to the human ear to be of equal importance. The equalizer, shown in Figure 1, has been made part of the equipment in order to modify its response to agree more nearly with that of the ear. The charts at the right of Figure 2 show how the vowel sounds *i* and *e* look when modified by the equalizer.

Interpreting the Charts

When studying speech sound patterns by the method just outlined, one needs to make numerous similar experiments before

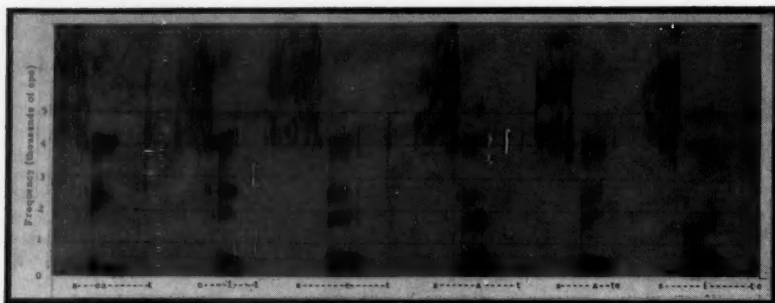


Figure 3. This sound spectrogram illustrates how even quite similar sounds are characterized by variations in their intensity at different frequencies.

he can safely conclude that the chart of any particular speech sound distinguishes it from all others. This fact can be illustrated by the charts shown in Figure 2 for the ϵ sound in *set*. Having only the chart at the lower left (made without the equalizer), one might be tempted to conclude that only the formant at 500 cps is important in characterizing the sound. Yet, when we examine the chart at the lower right of Figure 2, we observe that the equalizer has actually interchanged the relative intensities of the formants that appear just below 2,000 cps and 4,000 cps. Examination of similar sounds as produced by different speakers has indicated that the two lower frequency formants (at 500 cps and 2,000 cps) obtained with use of the equalizer are typical of the ϵ sound. The presence or absence of the highest formant (that at 4,000 cps) affects the quality of the sound, but it does not appear to change its interpretation.

One of the best ways to ascertain which features are significant in such charts is to study synthetically produced sounds, modifying them in various ways and determining the minimum number of attributes necessary to characterize them. Haskins Laboratories, Inc., has developed a device capable of synthesizing connected speech sounds from simple tones. When visibly analyzed sounds are carefully reproduced audibly by this device, they are quite understandable, although their quality is far from natural. As more and more details in its

spectrum are eliminated from the synthetically produced sound, its meaning is progressively lost. Considerable effort and experience are required to understand the unnatural sounds, and it often is difficult to decide at just what point the sounds become unintelligible. Thus, it is not easy to determine which sounds may properly be regarded as synthetic speech sounds and which have become associated with speech only through a learning process on the part of the experimenter.

The Sound Spectrograph

The spectrum analyzer that we have described can only be used to study sustained sounds. If each resonator channel were provided with its own volume indicator, all could be used simultaneously, and a continuous analysis would be obtained. In order to give meaning to the term *spectrum* when applied to sounds that are not stationary, a given time interval can be divided into very brief intervals during each of which the sounds are almost periodic. Each short interval can then be regarded as a sample of a proper periodic function. By means of this artifice, the spectrum can be represented as changing with time. While the results are admittedly somewhat inexact, they are still quite useful.

Bell Telephone Laboratories have recently developed a "sound spectrograph" for making visible analyses of short samples of speech. In one model of this device, the speech sample is repeatedly fed by means

of a specially designed tape recorder into a wave analyzer that automatically scans the spectrum from 0 to 8,000 cps. During this scanning process, a stylus marks an electrically sensitive paper in accordance with the output of the wave analyzer, indicating the intensity of each component by the darkness of the trace produced while recording the frequency by vertical distance on the chart and time by horizontal distance. The scales for frequency and time permit quite accurate measurement, but the measurement of intensity is essentially only qualitative because of the limited contrast provided by the recording paper. In another model of the sound spectrograph, different colors are used (instead of different degrees of darkness) to represent intensity.

Figure 3 shows the word sequence *seat, sit, set, sat, sate, site* as made visible by the sound spectrograph. The vertical striations represent the pitch-frequency variations in intensity; no equalizer was used.

In the case of such spectrograms, as well as in that of the vowel spectra charts, allowance must be made for the influence of machine characteristics. For example, the syllabic variation of intensity is largely obscured in the sound spectrograms.

As shown in Figure 3, the patterns of corresponding sounds are similar. Characteristic formant patterns are also indicated for consonant sounds, even very brief ones. Examination of many such spectrograms has led to the belief that each distinctly different sound can be associated with a particular combination of formant frequencies and types of excitation.

However, consonant sounds are not as readily characterized as the vowels, since the latter are sustained. Many vowel sounds display two major formants, and the ratio of the frequencies at which these formants appear is the principal factor considered in identifying them. As mentioned, the presence of other formants only affects the quality of vowel sounds without aiding in their identification. On the other hand, the formants of consonants tend to shift under the influence of the vowel sounds to follow, particularly in the case of stop consonants such as *p, t* and *k*. These sounds appear to be characterized more by their abruptness than by their formant frequencies.

Reading Sound Spectrograms

We have already seen that sounds converted into visual form by the spectrum analyzer or sound spectrograph can be reconverted into intelligible speech by a device such as that developed by Haskins Laboratories. Actually, training classes at Bell Telephone Laboratories have learned to read sound spectrograms directly, both when they are stationary and when they are slowly moved across a screen.

The ability to read sound spectrograms is not very surprising since visible speech patterns are really natural phonetic symbols, corresponding to the way sounds, syllables and words are spoken rather than to the way they are spelled. Different sounds have a different appearance; yet, the same sounds spoken by different people look alike. Both of these features are essential if sound spectrograms are to serve a practical use as phonetic symbols. Thus we find that we are able to record speech sounds visibly, thereby representing phones or phonemes, then to read them back, combining the sounds into syllables and the syllables into words.

Applications

Some experimenters have suggested that the sound spectrograph may eventually become a boon to the severely deafened, those whom hearing aids cannot help. Much research would be necessary before equipment compact enough and inexpensive enough could be provided to supplant lip reading as a means for the completely deaf to grasp the spoken word. Indeed, it seems that lip reading is likely to continue to be the severely deafened person's major way of comprehending the speech of those with whom he comes in daily contact. However, it does not seem unreasonable to believe that units could be built to make radio signals and the audio signals of television visible to the deaf, thereby greatly extending the horizons of their incoming communications. A similar unit might make it possible for deaf persons to use the telephone in the two-way manner that others do.

The sound spectrogram may come to have a significant place in the education of the deaf. Since its symbols are naturally

phonetic, it should serve as a means for teaching pronunciation, not an easy task when the pupil cannot hear the results of his efforts. In this case, while he still could not hear what he said, he could see what he said and could compare his pattern with that of his teacher. As pupils developed the ability to read sound spectrograms at a normal speaking rate, it is conceivable that classroom subjects might be taught using a viewing screen rather than relying on writing or observation of the teacher's lips.

There are numerous possibilities for use of the sound spectrograph in the study of phonetic problems, the physiology of speech, speech correction, foreign languages, vocal music, etc. Readers interested in discussion of these possibilities are referred to Bell Telephone Laboratories' book, "Visible Speech," written by R. K. Potter, G. A. Kopp and H. C. Green and published by D. Van Nostrand Company, Inc.

According to the book just mentioned, voice-operated typewriters should be capable of construction, since such a thing does not seem beyond the range of reasonable extrapolation from what has already been done. One can only guess what developments the future may bring in the field of acoustic phonetics. One thing seems certain, however—there is plenty of room for research in the field.

NEW PUBLICATION SCHEDULE

Since its inception in May, 1946, *The Research Engineer* has been published five times annually—the first issue of each publishing year in May, the second in September, and the remaining three at bimonthly intervals until the following March. Although this schedule allowed the editorial staff a respite for vacations in the summer months, it had little else to recommend it. *The Research Engineer*, while published at stated intervals, was not truly a periodical. Each year numerous readers wrote to request a supposedly missing July issue, and even librarians often required clarification of the admittedly confusing publication schedule.

DR. HERSCHEL H. CUDD NAMED ACTING DIRECTOR



Late in November, Dr. Herschel H. Cudd was appointed Acting Director of the Engineering Experiment Station to succeed Dr. Gerald A. Rosselot who recently resigned.

Dr. Cudd possesses a broad background of industrial research experience, including employment with du Pont's Rayon Technical Division, International Minerals and Chemicals Corporation and West Point Manufacturing Company. His research has brought him several patents in the fields of synthetic fibers and metallurgy, and he has other patent applications pending.

Although a Texan by birth and place of education, Dr. Cudd qualifies as a Georgian through more than a decade of residence here. He received his B.S. in Chemistry from Texas A.&I. in 1933 and his Ph.D. in Physical Chemistry from the University of Texas in 1941. He came to Georgia in 1942 to direct inorganic chemical research for International Minerals and Chemicals at East Point. He joined West Point Manufacturing Company's Research Division in 1946, and he was subsequently appointed Director of its Lantuck Division to supervise development, production and sales of new products stemming from his research. Early in 1950, Dr. Cudd was appointed head of the Engineering Experiment Station's newly formed Chemical Sciences Division, a position he will continue to fill until an equally able successor can be found.

Beginning with this issue, *The Research Engineer* will be a quarterly published in January, April, July and October. The so-called 1952-53 Volume, although not scheduled for completion until March, will be terminated in order that the January issue can be designated Volume 7, No. 1.

